Reversal of Fortune: Confirmation of an Increasing Star Formation-Density Relation in a Cluster at z = 1.62

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Abstract: We measure the rest-frame colors (dust-corrected), infrared luminosities, star formation rates, and stellar masses of 92 galaxies in a Spitzer-selected cluster at z = 1.62. By fitting spectral energy distributions (SEDs) to 10-band photometry (0.4 m< obs < 8 m) and measuring 24 m fluxes for the 12 spectroscopically confirmed and 80 photometrically selected members, we discover an exceptionally high level of star formation in the cluster core of 1700 M sun yr-1 Mpc-2. The cluster galaxies define a strong blue sequence in (U-V) color and span a range in color. We identify 17 members with L IR>1011 L sun, and these IR luminous members follow the same trend of increasing star formation with stellar mass that is observed in the field at z 2. Using rates derived from both the 24 m imaging and SED fitting, we find that the relative fraction of star-forming members triples from the lowest to highest galaxy density regions; e.g., the IR luminous fraction increases from 8% at Σ 10 gal Mpc-2 to 25% at Σ > 100 gal Mpc-2. The observed increase is a reversal of the well-documented trend at z < 1 and signals that we have reached the epoch when massive cluster galaxies are still forming a substantial fraction of their stars. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion laboratory, California Institute of Technology, under NASA contract 1407. This Letter also includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile. This work is based in part on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

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REVERSAL OF FORTUNE: CONFIRMATION OF AN INCREASING STAR FORMATION–DENSITY RELATION IN A CLUSTER AT $z = 1.62$*

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ABSTRACT

We measure the rest-frame colors (dust-corrected), infrared luminosities, star formation rates, and stellar masses of 92 galaxies in a *Spitzer*-selected cluster at $z = 1.62$. By fitting spectral energy distributions (SEDs) to 10-band photometry ($0.4\,\mu\mathrm{m} < \lambda_{\mathrm{obs}} < 8\,\mu\mathrm{m}$) and measuring 24 μm fluxes for the 12 spectroscopically confirmed and 80 photometrically selected members, we discover an exceptionally high level of star formation in the cluster core of $\sim 1700\,M_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-2}$. The cluster galaxies define a strong blue sequence in $(U-V)$ color and span a range in color. We identify 17 members with $L_{\mathrm{IR}} > 10^{11}\,L_\odot$, and these IR luminous members follow the same trend of increasing star formation with stellar mass that is observed in the field at $z \sim 2$. Using rates derived from both the 24 μm imaging and SED fitting, we find that the relative fraction of star-forming members triples from the lowest to highest galaxy density regions; e.g., the IR luminous fraction increases from ~8% at $\Sigma \sim 10$ gal Mpc^{-2} to ~25% at $\Sigma \gtrsim 100$ gal Mpc^{-2}. The observed increase is a reversal of the well-documented trend at $z < 1$ and signals that we have reached the epoch when massive cluster galaxies are still forming a substantial fraction of their stars.

Key words: galaxies: clusters: individual (ClG J0218.3-0510) – galaxies: evolution – galaxies: starburst – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

A well-established observational hallmark of how galaxies evolve as a function of environment is the star formation–galaxy density relation. A plethora of studies utilizing multi-wavelength tracers of activity have shown that star formation universally decreases with increasing galaxy density at $z < 1$ (e.g., Hashimoto et al. 1998; Ellingson et al. 2001; Gómez et al. 2003; Patel et al. 2009). In particular, the cores of massive galaxy clusters are galaxy graveyards full of massive spheroidal systems that are dominated by old stellar populations. However, as we approach the epoch when these quiescent behemoths should be forming the bulk of their stars ($z \gtrsim 2$; van Dokkum et al. 1998; Jørgensen et al. 2006; Rettura et al. 2010), the star formation–density relation should weaken and possibly reverse. Identifying when star formation is quenched as a function of galaxy mass and environment provides strong constraints on galaxy models (e.g., Kauffmann et al. 1993; Hopkins et al. 2008); i.e., is individual galaxy mass or the larger scale environment the primary driver of evolution?

Observations of field galaxies at $z \sim 1$ indicate that the star formation–density relation turns over at this epoch such that there is an enhancement of activity in the highest density regions of the field (Elbaz et al. 2007; Cooper et al. 2008). Studies also find an excess of dust-obscured star formation in group environments at $z < 1$ (Koyama et al. 2008; Tran et al. 2009; Gallazzi et al. 2009), and very recent results suggest that star formation may be enhanced in the significantly richer core of a galaxy cluster at $z \sim 1.46$ (Hilton et al. 2010). As cluster surveys push to higher redshifts ($z > 1$) and thus closer to the epoch when massive galaxies are forming their stars, variations in age will become evident in, e.g., a larger scatter in color, and robust star formation rates should reveal increasing levels of activity even in the cluster cores.

We report here the first confirmation of increasing star formation activity with increasing galaxy density observed in cluster ClG J0218.3-05101, a *Spitzer*-selected galaxy cluster at $z = 1.62$ (Papovich et al. 2010, hereafter Pap10). We use cosmological parameters $\Omega_m = 0.3$, $\Lambda = 0.7$, and $H = 70$ km s^{-1} Mpc^{-1} throughout the Letter; at $z = 1.62$, this corresponds to an angular scale of 0.5 Mpc arcmin^{-1}. All magnitudes are in the AB system.

2. MULTI-WAVELENGTH DATA

ClG J0218.3-0510 has a wealth of multi-wavelength imaging data that includes $BRi'z'$ imaging from the Subaru-XMM Deep

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Survey (Furusawa et al. 2008) and *JK* imaging from the UKIRT IR Deep Sky Survey (UKIDSS; Lawrence et al. 2007); for these data, we utilized the *K*-selected catalog from Williams et al. (2009). The cluster field also has deep *Spitzer* imaging available in the four IRAC bands (3.6–8.0 μm) and MIPS 24 μm as part of the *Spitzer* public legacy survey of the UKIDSS Ultra-Deep Survey (SpUDS; PI: J. Dunlop).[12] We matched the *K*-band selected catalog to the IRAC data following Papovich et al. (2006).

ClG J0218.3-05101 was originally detected as a strong overdensity of galaxies at $1.5 < z_{\rm phot} < 1.7$ with a mean surface density $>20\sigma$ higher than that of galaxies in the same redshift range in the UKIDSS Ultra-Deep Survey (Lawrence et al. 2007). Follow-up spectroscopy confirmed 10 members that define a narrow redshift peak at $1.622 \leqslant z \leqslant 1.634$ with additional members at $z = 1.609$ and $z = 1.649$ (Pap10; Tanaka et al. 2010). In our analysis, we include 80 more members that are selected from photometric redshifts determined with EAZY (Brammer et al. 2008); we use the limit for the integrated redshift probability defined by the spectroscopically confirmed members ($\mathcal{P}_z > 0.3$; see Pap10 for a detailed description of the photometric selection).

Analysis of *XMM-Newton* data in this field also reveals a weak detection consistent with extended emission from the cluster. The cluster mass estimated from its X-ray luminosity is $\sim 1.1 \times 10^{14}\ M_\odot$ and is consistent with its estimated dynamical mass of $\sim 4 \times 10^{14}\ M_\odot$. To define the cluster center, we select the massive (spectroscopically confirmed) member located at the peak of the X-ray emission: its J2000 coordinates are (2:18:21.07, −5:10:32.84), and all of the cluster galaxies lie within $R_{\rm proj} \sim 1$ Mpc of this member.

2.1. Spectral Energy Distributions

We fit the 10-band galaxy photometry ($0.4\,\mu{\rm m} < \lambda_{\rm obs} < 8\,\mu$m)[13] with the 2007 version of the Bruzual & Charlot (2003) stellar population synthesis models using a Chabrier initial mass function (IMF; for more details, see Papovich et al. 2006). We find that models with solar metallicity best reproduce the rest-frame colors and scatter of the cluster red sequence galaxies (Pap10), and we allow the models to range in age from 10^6 to 2×10^{10} yr; we also include dust attenuation using the Calzetti et al. (2000) law with color excess values ranging from $E(B-V) = 0.0$–0.7. We allow for a range of star formation histories parameterized as a decaying exponential with an *e*-folding time τ, where at any age t the star formation rate is $\Psi(t) \sim \exp(-t/\tau)$ and τ ranges from 1 Myr to 100 Gyr (corresponding approximately to instantaneous bursts to constant star formation, respectively). In the model fitting, we add a $\sigma/f_\nu = 5\%$ error in quadrature to the photometric uncertainties on each band to account for mismatches in the multi-band photometry, and for the fact that the models do not continuously sample the model parameter space. Our sample of 92 cluster members has an average best-fit age of $\sim$500 Myr and an average best-fit τ of $\sim$500 Myr; 35 members have SED-derived star formation rates $>5\ M_\odot\ {\rm yr}^{-1}$.

2.2. MIPS 24 μm Fluxes

The cluster field was imaged with *Spitzer* MIPS as part of the legacy UKIDSS Ultra-Deep Survey (SpUDS; PI: J. Dunlop).

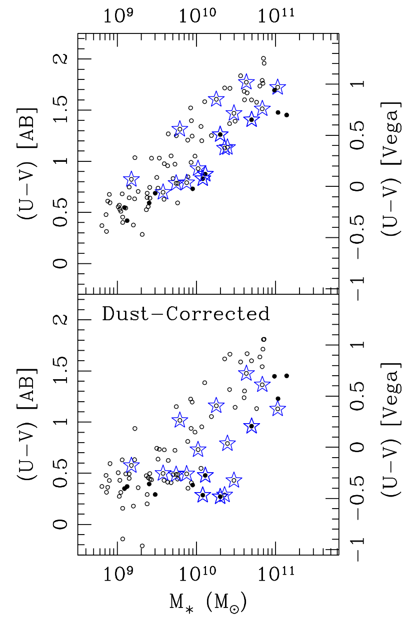

Figure 1. Rest-frame $(U-V)_{\rm AB}$ color vs. stellar mass determined from fitting SEDs (assuming Chabrier IMF) to the 10-band photometry: shown are the measured (top) and dust-corrected (bottom) color–mass diagrams. Open circles denote members selected using photometric redshifts from EAZY (Brammer et al. 2008) and filled circles denote spectroscopically confirmed members from Papovich et al. (2010) and Tanaka et al. (2010); the latter tend to be on the blue edge because the spectroscopy favors members with emission lines. The 17 cluster members detected at 24 μm are marked with open stars; note the number of IR luminous members that remain red even after being corrected for dust extinction. The ClG J0218.3-0510 members have a color distribution similar to that observed in the field at $z \sim 2$ (Brammer et al. 2009) and, in contrast to galaxy clusters at $z < 1$, the members populate a blue sequence and span a range in color.

(A color version of this figure is available in the online journal.)

We extracted sources from the public SpUDS 24 μm map using StarFinder (Diolaiti et al. 2000), an IDL-based point-spread function (PSF) fitting code designed for crowded fields. The 24 μm image has 1$''$.245 pixel^{-1}, and we derived a model PSF and aperture corrections from the brightest isolated sources from the SpUDS image. The catalog includes all sources detected with S/N > 5; this corresponds to a flux of $\sim$40 μJy. Using simulated sources based on the PSF and injected into the map, we determine that the catalog is 80% complete at this flux level.

The measured 24 μm fluxes are converted into total infrared luminosities ($L_{\rm IR}$) using the Chary & Elbaz (2001) templates. Recent Herschel studies indicate that while this technique is very accurate at $z < 1.5$, extrapolations from monochromatic 24 μm fluxes overestimate the true $L_{\rm IR}$ by factors of 2–7 at $z > 1.5$ (e.g., Nordon et al. 2010). Finally, star formation rates are calculated from $L_{\rm IR}$ using the prescription of Kennicutt (1998), adjusted to the Chabrier IMF.

3. STELLAR MASSES, STAR FORMATION RATES, AND ENVIRONMENT

By fitting SEDs to the 10-band photometry ($0.4\,\mu{\rm m} < \lambda_{\rm obs} < 8\,\mu$m), we are able to measure accurate rest-frame colors (AB system) and stellar masses as well as correct for dust extinction. Figure 1 shows the measured and dust-corrected rest-frame $(U-V)$ color versus stellar mass for the 92 cluster galaxies within $R_{\rm proj} \sim 1$ Mpc of the brightest galaxy cluster. As demonstrated by, e.g., Wyder et al. (2007), the galaxies begin to separate into the well-known bimodal distribution only when the colors are corrected for extinction.

[12] http://ssc.spitzer.caltech.edu/spitzermission/observingprograms/legacy/spuds/

[13] At $z = 1.62$, this corresponds to a rest-frame wavelength range of $0.15\,\mu{\rm m} < \lambda_{\rm rest} < 3.0\,\mu$m.

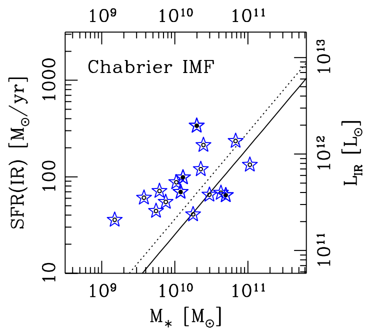

Figure 2. Star formation rate vs. stellar mass for 24 μm detected cluster galaxies at $z = 1.62$; symbols are the same as in Figure 1. The most strongly star-forming systems are also some of the most massive cluster members. These galaxies follow the same trend that is observed in field galaxies at $z \sim 2$ (fitted relation and upper semi-interquartile range of 0.16 dex shown as solid and dotted lines, respectively; Daddi et al. 2007). All 17 of the 24 μm detected members have $L_{IR} > 10^{11}\ L_\odot$, in stark contrast to the relative dearth of such massive, IR-bright galaxies in clusters at $z < 1$.

(A color version of this figure is available in the online journal.)

The ClG J0218.3-0510 members differ from their counterparts in clusters at $z \lesssim 1.2$ (e.g., Holden et al. 2006; Rettura et al. 2010) in that they have a color–stellar mass distribution that is surprisingly similar to that observed in the field at $z \sim 2$ (Brammer et al. 2009): the ClG J0218.3-0510 members define a strong blue sequence and span a range in (dust-corrected) color (Figure 2, bottom panel). While these members populate a red sequence in the $(z - J)$ color–magnitude diagram (Pap10), the correlation between rest-frame $(U-V)$ color and stellar mass is visibly weaker.[14] However, the most massive galaxies ($M_* \sim 10^{11}\ M_\odot$) are still the reddest, i.e., they have the oldest stellar populations.

Seventeen of the members are detected at 24 μm (Figure 1), and the most IR luminous members include some of the most massive cluster galaxies (Figure 2). Figure 2 shows that these IR luminous members follow the same trend of increasing star formation with stellar mass that is observed in the field at $z \sim 2$ by Daddi et al. (2007). Note that because we can only detect members that are IR bright ($L_{IR} \gtrsim 3 \times 10^{11}\ L_\odot$), we are sensitive only to the upper envelope of the trend observed at $z \sim 2$.

Three of the ClG J0218.3-0510 members are ultra-luminous infrared galaxies (ULIRGs; $L_{IR} \geqslant 10^{12}\ L_\odot$; see Figure 2) and the remaining 14 are LIRGs ($10^{11}\ L_\odot \leqslant L_{IR} < 10^{12}\ L_\odot$). In stark contrast, of the >2000 galaxies in clusters at $z < 1$ studied with wide-field ($R_{proj} \gtrsim 1$ Mpc) mid-IR imaging (e.g., Geach et al. 2006; Saintonge et al. 2008; Smith et al. 2010), only one is a ULIRG and it lies outside the core of the Bullet Cluster, a well-known cluster–cluster merger at $z = 0.297$ (Chung et al. 2010). The higher fraction of IR luminous galaxies at $z = 1.62$ is likely to be driven by the overall evolution of the IR luminosity function in clusters (e.g., Bai et al. 2009); however, more deep IR imaging of clusters at $z > 1$ is needed to confirm this trend.

In our analysis, we assume that the 24 μm sources are dominated by star formation and do not harbor active galactic nuclei (AGNs). From the SED fits, we find that two of the 24 μm detected members do have emission at 8.0 μm (IRAC channel 4) that deviates from the stellar fit, i.e., have a power-law component indicative of an AGN, and one of these galaxies is the most IR luminous member with $\log(L_{IR})$ $(L_\odot)$ ~12.3 (see Figure 2). However, studies find that most of the emission

[14] The astute reader will notice that the red sequence is tighter in $(z–J)$ color because these filters correspond approximately to rest frame $(U–B)$ at $z = 1.62$.

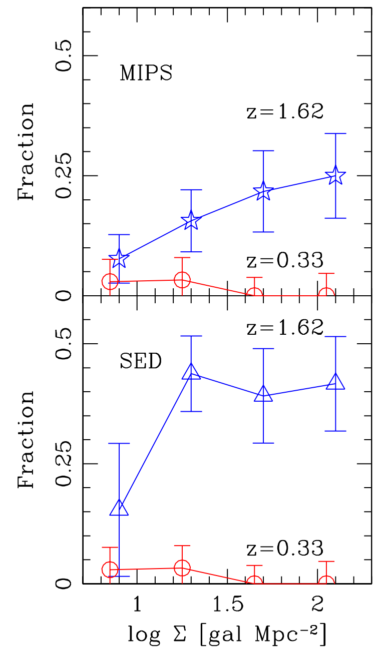

Figure 3. Relative fraction of star-forming cluster galaxies vs. local galaxy density for 24 μm detected members with star formation rates $\gtrsim 40\ M_\odot$ yr^{-1} (top; open stars) and members with SED-derived rates $>5\ M_\odot$ yr^{-1} (bottom; open triangles). The open circles in both panels show the 24 μm detected members in the massive galaxy cluster CL 1358+62 at $z = 0.33$ (Tran et al. 2009) and represent the well-established trend documented at $z < 1$; these circles are offset slightly in $\log \Sigma$ for clarity. Error bars are determined from bootstrapping the data in each bin 1000 times. The fraction of star-forming members is highest in the regions with the highest galaxy density, a reversal of the trend at $z < 1$. At $z = 1.62$, we have reached the epoch when massive cluster galaxies are still forming a significant number of new stars.

(A color version of this figure is available in the online journal.)

($\gtrsim$ 70%) in ULIRGs is due to star formation (Farrah et al. 2008), thus these members are likely to have both strong star formation and an AGN component. Note that at $z = 1.62$, the 7.7 μm polycyclic aromatic hydrocarbon band lies partly in the 24 μm channel.Because part of the IR luminosity is due to star formation, we include both 24 μm members in our analysis; repeating our analysis without these two members confirms that our overall results do not change.

In the cluster core (R_{proj} = 0.5 Mpc), the star formation rate density from the 24 μm photometry alone is $\sim$1700 $M_\odot$ yr^{-1} Mpc^{-2}; we stress that this is likely a lower limit given the 24 μm imaging that cannot detect any members with $\mathrm{SFR_{IR}} \lesssim 40\ M_\odot$ yr^{-1}, i.e., with star formation rates typical for IR-detected galaxies in clusters at $z < 1$. Only one other galaxy cluster at $z = 1.46$ has a comparably high star formation rate in its core (Hayashi et al. 2010; Hilton et al. 2010). In comparison, studies of IR-detected galaxies in clusters at $z < 1$ find that star-forming members are strongly segregated at $R_{proj} > 0.5$ Mpc (Geach et al. 2006; Saintonge et al. 2008; Koyama et al. 2008).

Given the high star formation rate in its core, does ClG J0218.3-0510 follow the well-established trend at $z < 1$ of decreasing star formation with increasing galaxy density (e.g., Hashimoto et al. 1998; Ellingson et al. 2001; Gómez et al. 2003)? Figure 3 compares the relative fraction of star-forming members to passive members as a function of local galaxy density (Σ) which is defined by distance to the 10th nearest neighbor (Dressler 1980). We use star formation rates derived from the 24 μm imaging as well as from the SED fitting because the two independent star formation tracers complement each other and provide an important check of our results: the 24 μm imaging is a robust measure of the dust-obscured star formation but only detects the most active members ($\gtrsim$40 $M_\odot$ yr^{-1}) while the SED fitting is sensitive to lower levels of unobscured activity ($\gtrsim$5 $M_\odot$ yr^{-1}).

Both star formation tracers confirm that the relative fraction of active members is highest in the regions of highest galaxy density (Figure 3), i.e., exactly opposite to that observed in clusters at $z < 1$. A Spearman rank test supports with >97% confidence (>2σ significance) that the relative fraction of IR luminous members increases with increasing galaxy density from ∼8% at $\Sigma \sim 10$ gal Mpc^{-2} to ∼25% at $\Sigma \gtrsim 100$ gal Mpc^{-2}. We stress that excluding the two candidate AGNs does not change the trend, and the robustness of this result is underscored by the fact that we see the same trend using the SED-derived rates. While studies of galaxies in the field at $z \sim 1$ ($\Sigma < 10$ gal Mpc^{-2}) find that the star formation–density relation is beginning to turn over at this epoch (Elbaz et al. 2007; Cooper et al. 2008), this is the first confirmation of such a reversal in the significantly higher density environment of galaxy clusters.

The measured IR luminosities correspond to specific star formation rates (SSFR; star formation rate divided by stellar mass) per Gyr of ∼1–20: these active members can more than double their stellar masses in the next Gyr (by $z \sim 1.2$). However, to reproduce the relatively homogeneous stellar ages measured in massive cluster galaxies at $z < 1$ (e.g., Blakeslee et al. 2006; Tran et al. 2007; Mei et al. 2009), these IR luminous members cannot maintain such a high SSFR even for a Gyr. The current star formation must be quenched rapidly and any later bursts of activity cannot add a substantial amount of new stars, at least not in the massive members ($\log(M_*)$ [$M_\odot$] > 10.6) that must populate a well-defined red sequence by $z \sim 0.8$.

4. CONCLUSIONS

We measure the rest-frame colors (dust-corrected), IR luminosities, star formation rates, and stellar masses of galaxies in ClG J0218.3-0510, a *Spitzer*-selected cluster at $z = 1.62$, by fitting SEDs to photometry in 10 bands (0.4 μm < $\lambda_{\rm obs}$ < 8 μm) and with deep 24 μm imaging. The cluster sample (Pap10; Tanaka et al. 2010) is composed of 12 spectroscopically confirmed members and 80 members selected from photometric redshifts measured using EAZY (Brammer et al. 2008); all members are within $R_{\rm proj} \lesssim 1$ Mpc of the massive cluster galaxy located at the peak of the X-ray emission.

The 92 cluster members have a color–stellar mass distribution that is surprisingly similar to that observed in field galaxies at $z \sim 2$. When corrected for dust, the cluster members define a strong blue sequence and span a range in color, indicating a substantial amount of recent and ongoing star formation in the cluster core. This dramatic level of activity is underscored by the 17 members detected at 24 μm. In the cluster core ($R_{\rm proj} < 0.5$ Mpc), the star formation rate density from the IR luminous members alone is ∼1700 $M_\odot$ yr^{-1} Mpc^{-2}; the true value is likely to be higher given that we only include members with SFR$_{\rm IR} \gtrsim 40$ $M_\odot$ yr^{-1}. These IR luminous members also follow the same trend of increasing star formation with stellar mass that is observed in the field at $z \sim 2$.

We discover the striking result that the relative fraction of star-forming galaxies increases with increasing local galaxy density in ClG J0218.3-0510, a reversal of the well-established trend at lower redshifts and in line with recent work at $z \sim 1.46$ that suggests enhanced star formation in cluster cores. Measurements using star formation rates derived from the 24 μm imaging and from the SED fitting provide independent confirmation that the relative fraction of star-forming galaxies triples from the lowest to highest density regions. By pushing into the redshift desert ($z \gtrsim 1.6$), we are able to reach the epoch when massive cluster galaxies are still forming a significant number of their stars.

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REFERENCES

Bai, L., Rieke, G. H., Rieke, M. J., Christlein, D., & Zabludoff, A. I. 2009, ApJ, 693, 1840
Blakeslee, J. P., et al. 2006, ApJ, 644, 30
Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, ApJ, 686, 1503
Brammer, G. B., et al. 2009, ApJ, 706, L173
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Calzetti, D., Armus, L., Bohlin, R. C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
Chary, R., & Elbaz, D. 2001, ApJ, 556, 562
Chung, S. M., Gonzalez, A. H., Clowe, D., Markevitch, M., & Zaritsky, D. 2010, arXiv:1005.3847
Cooper, M. C., et al. 2008, MNRAS, 383, 1058
Daddi, E., et al. 2007, ApJ, 670, 156
Diolaiti, E., Bendinelli, O., Bonaccini, D., Close, L., Currie, D., & Parmeggiani, G. 2000, A&AS, 147, 335
Dressler, A. 1980, ApJ, 236, 351
Elbaz, D., et al. 2007, A&A, 468, 33
Ellingson, E., Lin, H., Yee, H. K. C., & Carlberg, R. G. 2001, ApJ, 547, 609
Farrah, D., et al. 2008, ApJ, 677, 957
Furusawa, H., et al. 2008, ApJS, 176, 1
Gallazzi, A., et al. 2009, ApJ, 690, 1883
Geach, J. E., et al. 2006, ApJ, 649, 661
Gómez, P. L., et al. 2003, ApJ, 584, 210
Hashimoto, Y., Oemler, A. J., Lin, H., & Tucker, D. L. 1998, ApJ, 499, 589
Hayashi, M., Kodama, T., Koyama, Y., Tanaka, I., Shimasaku, K., & Okamura, S. 2010, MNRAS, 402, 1980
Hilton, M., et al. 2010, ApJ, 718, 133
Holden, B. P., et al. 2006, ApJ, 642, L123
Hopkins, P. F., Cox, T. J., Kereš, D., & Hernquist, L. 2008, ApJS, 175, 390
Jørgensen, I., Chiboucas, K., Flint, K., Bergmann, M., Barr, J., & Davies, R. 2006, ApJ, 639, L9
Kauffmann, G., White, S. D. M., & Guiderdoni, B. 1993, MNRAS, 264, 201
Kennicutt, R. C. 1998, ARA&A, 36, 189
Koyama, Y., et al. 2008, MNRAS, 391, 1758
Lawrence, A., et al. 2007, MNRAS, 379, 1599
Mei, S., et al. 2009, ApJ, 690, 42
Nordon, R., et al. 2010, A&A, 518, L24
Papovich, C., et al. 2006, ApJ, 640, 92
Papovich, C., et al. 2010, ApJ, 716, 1503
Patel, S. G., Holden, B. P., Kelson, D. D., Illingworth, G. D., & Franx, M. 2009, ApJ, 705, L67
Rettura, A., et al. 2010, ApJ, 709, 512
Saintonge, A., Tran, K.-V. H., & Holden, B. P. 2008, ApJ, 685, L113
Smith, G. P., et al. 2010, A&A, 518, L18
Tanaka, M., Finoguenov, A., & Ueda, Y. 2010, ApJ, 716, L152
Tran, K.-V. H., Franx, M., Illingworth, G. D., van Dokkum, P., Kelson, D. D., Blakeslee, J. P., & Postman, M. 2007, ApJ, 661, 750
Tran, K., Saintonge, A., Moustakas, J., Bai, L., Gonzalez, A. H., Holden, B. P., Zaritsky, D., & Kautsch, S. J. 2009, ApJ, 705, 809
van Dokkum, P. G., Franx, M., Kelson, D. D., & Illingworth, G. D. 1998, ApJ, 504, L17
Williams, R. J., Quadri, R. F., Franx, M., van Dokkum, P., & Labbé, I. 2009, ApJ, 691, 1879
Wyder, T. K., et al. 2007, ApJS, 173, 293